Theory and practice of evaporation measurement, with special focus on surface layer scintillometry as an operational tool for the estimation of spatially-averaged evaporation

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Abstract

A dual-beam surface layer scintillometer (SLS), for the estimation of sensible heat flux density every two minutes for a pathlength of 101 m, was used in a mixed grassland community in the eastern seaboard of South Africa for 30 months. The scintillometer relies on Monin-Obukhov stability theory, the correlation between the laser beam signal amplitude variances and the covariance of the logarithm of the beam signal amplitude measured using two detectors. Procedures for checking data integrity in real-time are high-lighted as are the post-data collection rejection procedures. In addition to the SLS sensible heat flux density measurements, an energy balance system was used to measure the soil heat flux density and the net irradiance from which the latent energy flux density (evaporation) was calculated as a residual. The SLS estimates of sensible heat flux density and evaporation are favourably compared against those obtained using the Bowen ratio and eddy covariance methods.

Keywords: *evaporation measurement, scintillometer, Bowen ratio, eddy covariance.*

1 Introduction

1.1 Background

The 1998 Republic of South Africa National Water Act refers to the possible prescription, by government, of methods for making a volumetric determination of water for purposes of water allocation and charges in the case of activities resulting in stream flow reduction. Given this scenario and the demand on water resources it is important to consider how evaporation, one of the main components of the water balance, is to be measured or estimated routinely with reliable accuracy and precision (Savage et al., 2004). Determination of reliable and representative data on evaporation is an important issue of atmospheric research with respect to applications in agriculture. Long-term measurements of evaporation at different time scales and from different climate regions are not yet readily available.

Point (single-level), profile and line-averaged atmospheric measurements have been used to measure sensible heat. Sensible heat is driven by vertical temperature differences between the canopy or soil surface and overlying air. By contrast, latent energy (evaporation) is driven by vertical water vapour pressure differences between just above the canopy or soil surface and that of overlying air. Sensible heat H and latent heat LE (evaporation) are important components of the shortened energy balance for a flat extensive surface: $I_{net} + H + LE + F_{soil} = 0$ where I_{net} is the net irradiance and F_{soil} the soil heat flux density. Hence LE may be estimated as a residual by measurements of the terms on the right hand side of $LE = -I_{net} - H - F_{soil}$.

Commonly, evaporation is estimated from grass reference evaporation (Allen et al., 1998: FAO 56) based on point atmospheric measurements at a single level at an automatic weather station: solar irradiance, air temperature, water vapour pressure and wind speed. In addition, a crop factor is used as a multiplying factor for reference evaporation to obtain the actual evaporation, the crop factor effectively distinguishing the vegetation under consideration from a grass reference crop. The dual crop factor approach uses one crop factor for the soil surface and another for the basal crop cover.

A scintillometer is used to measure line-averaged sensible heat flux density H. It measures the intensity fluctuations of visible or infrared radiation after propagation above the plant canopy of interest. It optically measures a parameter associated with refractive index fluctuations of air, C_n^2 (Thiermann, 1992), reflecting the atmospheric turbulence structure. Using what is referred to as Monin-Obukhov similarity theory (MOST), the sensible heat flux density H may be estimated. The MOST is empirically based. Surface layer scintillometers (SLS) operate over horizontal distances between 50 and 250 m. Large aperture scintillometers (LAS) operate over typical distances between 250 m and up to 3 km.

1.2 Shortened Energy Balance

There are many methods used for estimating evaporation (Table 1). As mentioned by Drexler et al. (2004) in their recent review, very few of the evaporation estimation methods work well for an hourly time-step, and in some cases, do not work well even for a daily time-step. There is perhaps only one method that allows for the direct measurement of the total water loss from a vegetated surface (soil evaporation plus transpiration). Virtually all of the methods rely on a theoretical framework for arriving at an expression for the latent energy flux density, in terms of other measurable quantities, based on certain assumptions or approximations. Many of the methods invoke use of a simplified surface energy balance equation:

$$I_{net} + LE + H + F_{soil} = 0$$

where I_{net} is the net irradiance (W m^{-2}), LE is the latent (evaporation) energy flux density (W m^{-2}), H is the sensible heat flux density (W m^{-2}) and F_{soil} is the soil heat flux density (W m^{-2}). The specific latent energy of vapourisation $L \simeq 2.43$ MJ kg^{-1}.

1.3 Energy Balance Closure

If components of the energy balance are measured independently and correctly, then $I_{net} + LE + H + F_{soil} = 0$ should be satisfied and closure is said to be satisfied. However, the condition could still be satisfied even if two or more terms have incorrect value and that fortuitously the terms still sum to 0 W m^{-2}. It would be inconceivable however that an incorrect set would always sum to 0 W m^{-2} for each time interval. Use of the energy balance equation for independent measurements of the component terms results in:

$$I_{net} + LE + H + F_{soil} = c$$

where c is termed the energy balance closure (W m^{-2}). Closure is said to be satisfied if $c = 0$ W m^{-2}. A non-zero value for c may be due to measurement errors in one or more of the component energy balance terms, although a near-zero value for c may be due to two or more of the component terms with incorrect value tending to cancel each other: as pointed out by Stannard et al. (1994), a near-zero value for c only increases confidence in the flux density measurements but does not necessarily verify them.

The spatial scales of the measurements for the component energy balance terms are different due to the nature of their measurement. For example, the source area of soil heat flux density measurements using a heat flux plate which is small in area, is very much less than 1 m^2. A net radiometer at measurement height of 2 m above canopy with a source area radius of 6 m is equivalent to a footprint measurement area of 113 m^2. The EC measurements of sensible heat flux density are point measurements influenced by downwind source areas. The differing spatial scales of measurements tend to counter the achievement of closure especially for heterogeneous terrain (Stannard et al., 1994).

1.4 Closure Not Satisfied?

For their relatively homogeneous terrain, Savage et al. (1997) found that the average closure value $\bar{c}$ was positive. For their heterogeneous terrain using eddy covariance (EC) measurements, Stannard et al. (1994) also found that the mean closure value $\bar{c}$ was positive. Stannard et al. (1994) listed a number of possible mechanisms associated with $\bar{c} > 0$ W m^{-2}:

- the magnitude of one or both of H and LE is underestimated;
- the available energy flux density, $I_{net} + F_{soil}$, is overestimated;
- the sensible heat or latent energy content, or both, of the air advected into the source area of the flux density measurements by the mean wind speed is less than that leaving the source area (-horizontal flux divergence);
- mismatched source areas for the different measurements of the energy balance component terms.

Stannard et al. (1994) reasoned that the influence of horizontal flux divergence on $\bar{c}$ would be small. They reasoned that divergence of sensible heat flux density would tend to be opposite in sign to the divergence of latent energy flux density since wetter areas tended to be cooler and drier areas tended to be warmer. Therefore in total, these divergences would tend to be nullified. They concluded that a detailed network of air temperature, relative humidity and wind speed sensors would be required to determine the net effect of divergence at any site. They also concluded that the underestimation of sensible heat and latent energy flux densities were the major cause of the tendency for $\bar{c}$ to be positive.

If closure is not satisfied, then $I_{net} + F_{soil} > -LE - H$. Another measure of the lack of closure is the closure ratio, which is given by:

Table 1[1]. Selected methods used for measurement or estimation of sensible heat H and/or latent energy flux density (evaporation) LE terms of the surface energy balance where $I_{net} + LE + H + F_{soil} = 0$.

Method	Measurement distance or area	Averaging period	Theoretical basis/comment	Closure statement/ comment
Class A-pan/ Symon's tank	< 5 m^2	Usually daily	$LE_{lysimeter} = L\,\rho_w\,(\delta W/\delta t)/A_{pan}$ where ρ_w is the density of water, $\delta W/\delta t$ is the rate of change in lysimeter weight and A_{pan} is the pan area	Only pan evaporation measured (historical merit only)
Lysimetry	< 10 m^2	Usually 20 to 60 min	$LE_{lysimeter} = L\rho_w\,(\delta W/\delta t)/A_{lysimeter}$	By definition, $H = LE - I_{net} - F_{soil}$
Micro-lysimeter	< 1 m^2	Usually daily	$LE_{lysimeter} = L\rho_w\,(\delta W/\delta t)/A_{lysimeter}$. Used for measuring soil evaporation	By definition, $H = LE - I_{net} - F_{soil}$
Bowen ratio (BR) energy balance (BREB)	Vertical measurement distance of 1 m (grassland) to 2 m for forests	Usually 20 to 30 min	$LE = \frac{-I_{net} - F_{soil}}{1+\beta}, 1+\beta \neq 0$ where β is the Bowen ratio; $H = \beta LE$	By definition, $-LE - H = I_{net} + F_{soil}$ Assumes equality between exchange coefficients: $K_h = K_w$
Eddy cov-ariance (EC) (2 sensors)	Sensor path length of 100 to 150 mm	Usually between 20 and 60 min	$LE = -\rho c_p \overline{w'e'}$, $H = -\rho c_p \overline{w'T'}$ (ρ is the air density and w', e' and T' are fluctuations in vertical wind speed, water vapour pressure and air temperature respectively	Generally, $-LE - H < I_{net} + F_{soil}$
EC (1 sensor)	Sonic path length of 100 to 150 mm	Usually between 20 and 60 min	$H = -\rho c_p \overline{w'T'}$ $LE = -H - I_{net} - F_{soil}$	By definition, $-LE - H = I_{net} + F_{soil}$
Surface layer scintillo-meter (SLS)	SLS beam length between 50 and 250 m	2 min and 60 min	Monin-Obukhov similarity theory (MOST) used to estimate H and LE estimated using $LE = -H - I_{net} - F_{soil}$	By definition, $-LE - H = I_{net} + F_{soil}$
Large aperture scintillometer (LAS)	Generally 500 m < beam length < 3.5 km (up to 10 km for boundary layer scintillometers (BLS)	2 min to 60 min	Measures C_n^2 , the structure parameter for refractive index fluctuations; MOST is assumed	By definition, $-LE - H = I_{net} + F_{soil}$
Surface renewal (SR)	Point measurement at a defined height above the surface	2 min and 60 min	$H \propto$ amplitude of the air temperature ramps/(ramp period)	By definition, $-LE - H = I_{net} + F_{soil}$
Temperature variance	Point measurement of the friction velocity and the standard deviation in air temperature at a defined height above the surface	30 min	$H \propto \sigma_T$ and u_* where σ_T is the temporal air temperature standard deviation and u_* is the friction velocity (m s^{-1}); MOST is assumed	By definition, $-LE - H = I_{net} + F_{soil}$
Temperature method	Point measurement of u_* and air temperature at a defined height above the surface	30 min	H is related to the weighted average of the time history of air temperature and u_*	By definition, $-LE - H = I_{net} + F_{soil}$ K theory is assumed
Reference evaporation	Point measurements of solar irradiance, and air temperature, wind speed and water vapour pressure at 2 m	Hourly/ daily	Penman-Monteith method for estimating reference evaporation (FAO 56), and use of a crop factor	Only reference evaporation and estimated crop evaporation estimated
Infrared technique	Areal measurement (< 25 m^2) of canopy temperature and wind speed	Hourly	Fick's Law to estimate sensible heat flux density	By definition, $-LE - H = I_{net} + F_{soil}$

[1] Taken from Savage et al. (2004)

Table 1 (continued). Selected methods used for measurement or estimation of sensible heat H and/or latent energy flux density (evaporation) LE terms of the surface energy balance where $I_{net} + LE + H + F_{soil} = 0$.

Method	Measurement distance or area	Averaging period	Theoretical basis/comment	Closure statement/ Comment
Atmometer (e.g., ET-gauge)	Point measurement at 1-m height above soil surface	Hourly	Empirical, with material cover of known pore size or known material	Only reference evaporation measured
Heat pulse /sap flow	Measurements made in or surrounding the stem of plants (< 200 mm)	Hourly	Rate of movement of stem heat pulse; stem energy balance with continuous heat applied	Transpiration measurements only
Cut stem technique	Destructive weight measurements of a plant part	Hourly	Change in weight per unit time = transpiration rate	Transpiration measurement estimates only

$$CR = \frac{-LE - H}{I_{net} + F_{soil}}$$

for which a closure ratio of 1 yields the shortened energy balance equation: $I_{net} + LE + H + F_{soil} = 0$

Ham et al. (2003) found that the energy imbalance persisted in different surfaces with an average of about 20 % but that the energy balance closure was better on average in the afternoon than in the morning, possibly suggesting the underestimation of storage terms, which are usually larger in the morning.

In the case of the BR technique, for which by definition β = H/LE, and invoking the energy balance yields

$$LE = \frac{-I_{net} - F_{soil}}{1+\beta}, 1+\beta \neq 0 ,$$

the closure ratio is necessarily always 1. Other methods for estimating sensible heat flux density used in this work such as the EC and surface layer scintillometer (SLS) methods involve measurements of H and estimation of LE by assuming a closure ratio of 1. The EC systems that measure H and LE independently of each other make no assumption of the value of the closure ratio.

1.5 Some Methods for Estimating Evaporation

Methods, such as the eddy covariance (EC) method, involve the measurement of two atmospheric variables and a theoretical framework and assumptions that allow for the direct calculation of the latent energy flux density LE. Other methods, such as the Bowen ratio (BR) method, involve up to eight measurements and a theoretical framework and assumptions to estimate sensible heat H and latent energy flux density LE (Savage et al., 2004). There are many empirical methods, not listed in Table 1, used to estimate the grass reference evaporation which use the crop factor approach to calculate evaporation.

The weighing lysimetric method is often regarded as the standard for evaporation measurement (Table 1). Weighing lysimeters are large containers, filled with soil, water, other chemicals and entire plant(s). Weight measurements are made at regular time intervals. The weight difference per unit time difference (in s, min, h or day) divided by the density of water (1000 kg m^{-3}) and divided by the cross-sectional area (m^2) of the lysimeter yields the evaporation rate in mm s^{-1}, mm min^{-1}, mm h^{-1} or mm day^{-1}. Lysimeters allow the water loss from such containers to be measured for very short time intervals and longer from hours to days or longer. The main component of water loss from a lysimeter is due to transpiration by plants and evaporation from the exposed soil surface. The disadvantages of the lysimetric method include: cost, destructive nature of the measurements in the sense that a relatively large volume of disturbed or sometimes undisturbed soil is placed in a container usually of metal construction and the non-portable nature of the measurement method. Also, the representation or the so-called footprint of the evaporation measurement is localised to the cross-sectional area of the lysimeter. Much less expensive is the microlysimetric method but the surface area is an order of magnitude less than a large weighing lysimeter and it is still a destructive method and not designed to contain whole plants. The more portable and much less invasive EC and BR methods used for the estimation of sensible heat and latent energy flux density by measurements above the surface are more popular research methods for the estimation of evaporation (Table 1). They are both portable systems that can be used to collect unattended measurements for extended periods of time. These methods were the focus of previous research reports (Savage et al., 1997, 2004).

1.6 Differing Footprints the Cause for the Lack of Closure?

Given the previously-mentioned limitations of the lysimetric method, the search for an alternative standard for evaporation estimation has been the focus of many studies for several decades. The EC and BR methods essentially yield point estimates of sensible heat and latent energy flux density although these estimates are influenced by events upwind from the point of measurement. In the case of sensible heat measurements, the measurement footprint refers to the relative contribution of

upwind surface sources to the sensible heat flux density measured at a height above the canopy surface. The extent of the footprint area of influence on the measurement using both EC and BR methods has received attention. For example, Savage et al. (1996, 1997) investigated the footprints of EC measurements and Stannard (1997) investigated the footprints of BR measurements. Agreement between BR and SLS measurements, for example, may be dependent on the footprint of the measurements.

The literature reports on the inadequacy of the EC technique for the direct estimation of latent energy flux density (Wilson et al., 2002; Ham and Heilman, 2003) with the result that the magnitude of the sum of sensible heat and latent energy flux density may be less than the sum of the net irradiance and soil heat flux density (Table 1) resulting in a closure ratio less than 1. This situation is referred to as a lack of closure. As an alternative therefore, the EC method could be used to measure the sensible heat flux density from which the latent energy flux density may be estimated from simultaneous measurements of soil heat flux density, net irradiance and the measured EC sensible heat flux density.

Each of the methods presented in Table 1 result in measurements with different footprints. The footprint of the lysimetric measurements is the area of the lysimeter. In the case of the EC method, the footprint is defined as the relative contribution of upwind surface sources to the measured sensible heat flux density.

By theoretical definition and making certain assumptions, the BR measurements always produce exact closure (Table 1). Due to a number of theoretical and practical problems we investigated the use of a SLS for the spatially-averaged measurement of sensible heat flux density and the estimation of latent energy flux density using soil heat flux density and net irradiance measurements. Problems associated with EC and BR methods include the following:

- that EC measurements of latent energy flux density are often underestimated, as claimed by a number of authors (for example, Twine et al., 2000);
- that both the EC and the BR estimates of latent energy are based on point measurements;
- that due to the theoretical assumptions made using the BR technique, exact measurement comparisons between the BR and EC measurement techniques have been frustrated by differing assumptions, differing footprint areas, measurement limitations and often-times poor agreement;
- a comparison of two methods does not indicate which method is correct especially if the methods disagree or disagree some of the time.

The SLS measurement method would remove the limitation of point estimates. The use of the SLS is the only method that supposedly allows for the estimation of sensible heat flux density over distances between 50 and 250 m. The frequency of SLS measurements is typically 1 kHz compared to 10 Hz for EC measurements, 1 Hz for BR measurements and 125 Hz for BLS measurements if the crosswind measurements are included. Because of the high frequency of the SLS measurements, the averaging period for SLS measurements can be as low as 1 or 2 min compared to the commonly used 20 min for EC and BR averaging periods (Savage et al., 2004).

Most of the published studies undertaken agree that the SLS method is a useful, robust and accurate method for obtaining a path-averaged estimate for sensible heat flux density for beam path lengths between 50 and 250 m. The major limitation is that of saturation under conditions of strong turbulence, necessitating using shorter beam path lengths and higher beam heights than that used when saturation occurs. However, many of the studies employing the SLS method have been very short in duration - in some cases for a few days and in other cases for a couple of months – and have not in detail compared the scintillometer method with eddy covariance and Bowen ratio measurement methods.

The objective of this work is to present the technical aspects of the SLS method for the estimation of evaporation for a mixed grassland community for an extended period of time. The methodology for the measurement of sensible heat flux density and the subsequent estimation of latent energy flux density is presented. A comparison is made between SLS, Bowen ratio and eddy covariance methods of estimating sensible heat and evaporation for a mixed grassland community for a period exceeding six months. Also, procedures and definition for rejection of out-of-range and bad or "doubtful" data are presented.

2 Materials and Methods

2.1 Site Details

Field measurements were conducted from Jan 2003 to June 2005 above an open and mixed grassland community summer rainfall site in the Hay Paddock area neighbouring Ashburton and close to Pietermaritzburg, South Africa (29^o 38' S, 30^o 26' E) with an altitude of 671.3 m (Fig. 1). There were occasional power problems and interruptions due to fire and accidental cutting of cables. The BR measurements commenced in Dec 2004. The average slope of the study site (Fig. 1, right) is 1o 15' to the SE. The minimum fetch distance for the site in the prevailing S-E wind direction is 135 m for the EC system and 90 and 138 m for the SLS transmitter and receiver respectively. The minimum fetch for the next-most dominant winds from the N-W is 117 m for the EC system and 146 and 114 m for the SLS transmitter and SLS receiver respectively. Beyond these distances and to the south, the site is exposed and the slope increases and the site adjacent to mixed grassland with occasional trees. To the north-west of the study area, there is a residential area and tall trees.

2.2 Surface Layer Scintillometer Measurements

A dual-beam surface layer scintillometer (model SLS40-A, Scintec Atmospärenmessetechnik, Tübingen, Germany), referred to as the SLS system (Thiermann, 1992; Thiermann and Grassl, 1992), was used to measure the sensible heat flux density

every 2 min for a beam distance of 101 m and a beam height between 1 and 1.6 m above the soil surface. The SLS40-A receiver has four detectors with two of the detectors used for automatic identification of and correction for transmitter vibration by the software used for analysis. In other words, the SLS40-A dual-beam system and its four detectors enable the separation and correction for the intensity fluctuations caused by beam movement. There are two detectors per beam. The SLS employs a diode laser source with an output wavelength of 670 nm and 1 mW mean output power (2 mW peak). The beam displacement and detector separation distances are 2.5 mm each, with a detector diameter of 2.7 mm. Software together with the instrument allows on-line measurements at a frequency of 1 kHz and subsequent calculation every 1 or 2 min of the structure parameter for refractive index fluctuations (C_n^2, $m^{-2/3}$), structure parameter for temperature (C_T^2, K^2 $m^{-2/3}$), the inner scale of turbulence $\boldsymbol{l_o}$ as indicated by the inner scale of refractive index fluctuations lo, mm), kinetic energy dissipation rate (ε, m^2 s^{-3}), sensible heat flux density (H, W m^{-2}), momentum flux density (τ, Pa) and the Monin-Obukhov length (L, m). Monin-Obukhov similarity theory (MOST) is assumed.

2.3 Bowen Ratio Measurements

Bowen ratio (BR) systems, modified after the 023A system of Campbell Scientific Inc. and connected to a Campbell 21X datalogger, were used to measure air temperature and water vapour pressure profile differences between heights of 1.55 and 2.96 m above the soil surface. The water vapour pressure profile measurements were obtained using one or more of: a HMP45C Vaisala air temperature and relative humidity sensor, a cooled mirror Dew-10 hygrometer, a CS500 Vaisala air temperature and relative humidity sensor.

Air temperature was measured at two levels using 75-μm type-E thermocouples. At each level, a parallel combination of 75-μm thermocouples was used. Extra insulation was used to cover the thermocouple connectors at the thermocouple join. Extra precautions were taken to cover and thermally insulate the point at which the thermocouple wires were connected to the datalogger. The thermocouples were regularly inspected for damage, cleanliness, insects and cobwebs.

For measuring the remaining components of the energy balance, three Q*7 (REBS, Seattle, Washington, USA) net radiometers placed at 2 m above the soil surface were used to measure net irradiance. Seven soil heat flux plates (model HFT-3, REBS) were used to measure soil heat flux density at a depth of 80 mm and a system of parallel thermocouples at depths of 20 and 60 mm used to calculate the soil heat flux density stored above the plates (Tanner 1960). Volumetric soil water content in the first 60 mm of the surface was measured using a frequency domain reflectometer (ThetaProbe, model ML2x, Delta-T Devices, Cambridge, UK) and a 615 soil reflectometer (Campbell Scientific). Most of these sensors were connected to a Campbell CR7X datalogger and transferred to a CR23X datalogger after the 2003 accidental fire. Measurements were every 1 s and averages obtained every 2 min which were in turn used to calculate 20-min averages for the BR calculations. The net radiometers, soil heat flux plates, infrared thermometers for canopy temperature (model IRTS-P, Apogee Instrument Inc., Logan, USA), and other EC sensors were positioned approximately midway between the transmitter and receiver units of the SLS40-A scintillometer.

2.4 Eddy Covariance Measurements

Adjacent to the automatic weather station, a three-dimensional sonic anemometer (SWS-211/3V, Applied Technologies, Boulder, USA), referred to as the ECAT system was used as an EC system to measure the sensible heat flux density at a height of 1.45 m above the soil surface. Late in the study, the measurement height was increased to a height above soil surface of 2.12 m. This anemometer, with a 100-mm sonic path length, was connected to a digital to analogue converter that then connected to a 21X datalogger (Campbell Scientific, Logan, USA). Measurements of the three components of wind velocity, u, v, w in the x, y and z directions respectively and sonic temperatures T were performed every 0.1 s (frequency of 10 Hz). Following the accidental fire (day of year 227, 2003), the 21X data logger was replaced by a Campbell CR23X datalogger and a replacement three-D sonic anemometer was used (same model). The sonic anemometer measurements were processed on-line and the two-min covariance between w and T (for determining sensible heat flux density H) and the covariance between w and the horizontal wind speed $U = (u^2 + v^2)^{0.5}$ (for determining momentum flux density τ) were calculated using c_p = 1136.3 J m^{-3} K^{-1} and ρ = 1.12 kg m^{-3}). The two-minute averages of u, v, w and sonic temperature T and wind direction $\theta = \arctan(v/u)$ were also stored. For a limited time, net irradiance (model Q*7 net radiometer), vertical wind speed and air temperature were sampled every 0.2 s using a Campbell CA27 one-dimensional sonic anemometer and fine wire thermocouple, respectively, and data processed using a Campbell 21X datalogger and two-minute averages, standard deviations and covariances stored for further data analysis. Data rejection rules were fairly simple: sometimes, usually whenever there was condensation, covariances of -99999 were excluded. Missing values and also periods when incorrect sonic temperatures approaching 50 ^oC were also used to exclude sensible heat data. These incorrect values were caused by dirt on the sonic transducers or faulty transducers. Nighttime EC measurements were often unreliable due to condensation or mist affecting the acoustic signal.

Calibration of the ECAT system and its replacement was performed by placing the 3D system in a box for which each component of the wind speed was 0 m s^{-1}. The air temperature and relative humidity, required for accurate speed of sound estimation (from which the sonic temperature is calculated), was independently measured using averaging thermocouples and a Vaisala CS500 air temperature and relative humidity sensor placed inside the box.

A fast responding water vapour pressure and carbon dioxide concentration sensor (LI-7500, LI-COR Inc., Lincoln, USA) and a second Applied Technologies 3-D sonic anemometer (model SATI/3V) with a sonic path length of 150 mm were used to

calculate the following flux densities using the EC technique: sensible heat, latent energy, momentum, and carbon dioxide. This system is referred to as ECopen.

3 Results and Discussion

3.1 Rejection Criteria for the Exclusion of Out-of-Range and "Bad" or Doubtful SLS Data

Data rejection or filtering procedures (Savage et al., 2004) were applied in a spreadsheet (Microsoft Excel) to the sensible heat flux density 2-min values. Sensible heat flux density H values were rejected, blanks were created or data recalculated:

- if the percentage of 1 kHz error-free data (EFD) was less than or equal to 25 % (EFD < 25 % - most-often for misty conditions), data were rejected;
- if the inner scale of refractive index fluctuations $\boldsymbol{l}_o$ was less than or equal to 2 mm, data were rejected;
- for missing data, designated by zeros, a blank cell was used for H;
- for positive dT/dz values, where dT/dz is the profile air temperature gradient measured using BR thermocouples, corresponding to unstable atmospheric conditions, EFD > 25 % and $\boldsymbol{l}_o$ > 2 mm and non-blank sensible heat flux density values, $-H_{day}$ is displayed in the cell;
- for stable atmospheric conditions, corresponding to dT/dz < 0 K m^{-1}, and EFD > 25 %, and $\boldsymbol{l}_o$ > 2 mm, $-H_{night}$ is displayed in the cell.

3.2 Flux Comparisons

3.2.1 Averaging Periods

The averaging periods for the various measurement systems are two minutes for EC, energy balance, reference evaporation, SLS and SR systems, 20 min for the BR system and 30 min for the open path EC system (ECopen). The 2-min averages are easily scaled to 20 min, 30 min and daily time intervals but the reverse is not possible.

3.2.2 EC (2-min) *vs* EC (20-min) Sensible Heat Flux Density Comparisons

The EC technique is often regarded as the standard for flux measurements against which all comparisons of sensible heat flux density are usually made. Initially, EC measurements were made at intervals of 20 min using the CA27 EC system consisting of a one-dimensional sonic anemometer and a fine-wire thermocouple. A field experiment using two EC systems was conducted with one system performing the covariance every 20 min and the other every 2 min. The 2-min sensible heat flux densities were averaged over 20 min and compared with the flux densities determined for the 20-min time period (Fig. 1a). The correspondence is good and this partly justifies using the 2-min time period for the EC method.

3.2.3 EC and SLS 2-min Sensible Heat Flux Density Comparisons

Generally, the agreement between 2-min SLS and ECAT sensible heat flux density values, as depicted by diurnal variations, was very good (data not shown). This is in spite of the SLS yielding path-averaged measurements and the ECAT value essentially yielding point measurements, different footprints for the SLS and ECAT measurement techniques, and the different measurement heights. The ECAT point measurements show a marked variation from one 2-min measurement to the next whereas there is a much reduced variation in the corresponding line-averaged SLS measurements. The correspondence between the two measurement methods is improved on most days under conditions when there is reduced turbulence, particularly on uniformly cloudy days and times before 10 am and after 2 pm (data not shown). On some days, the SLS

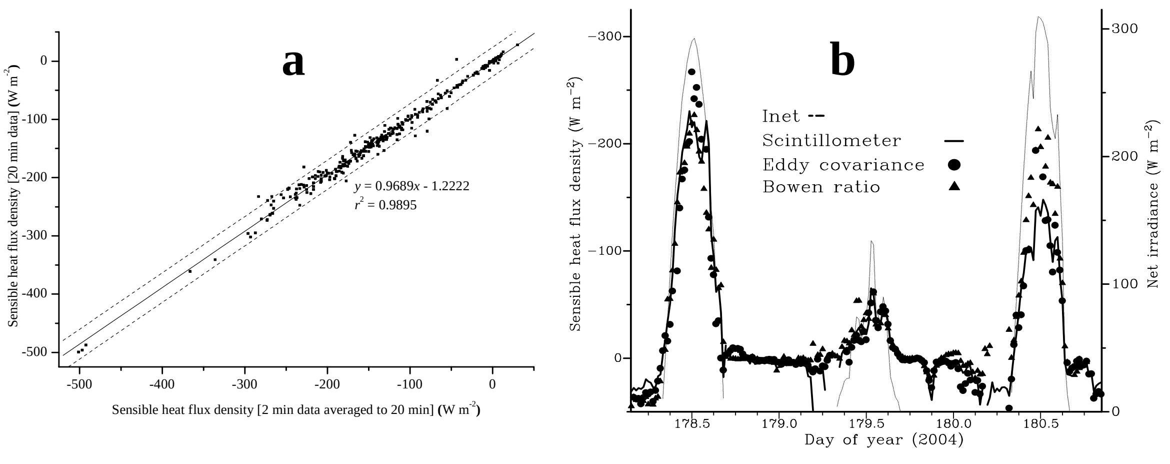

Figure 1. (a, left) A comparison between eddy covariance sensible heat flux density (CA27 system) measured using 20-min averaging and 2-minute averaging then averaged to 20 min.
(b, right) Diurnal comparisons between the three methods (SLS, EC and BR) for estimating sensible heat flux density H for a three-day period (4 to 6 June, 2004). Also shown, right-hand y-axis, is the net irradiance.

measurements were about midway between the ECAT highs and lows, the ECAT measurements were sometimes greater in magnitude than the SLS measurements and yet smaller in magnitude for other days. There no evidence for a consistent underestimation in sensible heat measurements by the EC method compared to the SLS measurements over and extended period of time. Furthermore, there is no evidence to indicate that the incorrect effective beam height input was incorrect (Cain et al., 2001). An incorrect input would have caused a consistent overestimation or underestimation in the SLS sensible heat measurements compared to EC measurements: the results of the error analysis showed that a fractional error in the beam height of 5 % would result in a sensible heat flux density fractional error of 4 %.

3.2.4 Comparison of SLS, Eddy Covariance (EC) and Bowen Ratio (BR) Sensible Heat Measurements

Comparisons between the three methods for estimating sensible heat flux density H are shown (Fig. 1b) for a three-day period (4 to 6 June, 2004). Radiative conditions varied from cloudless to scattered cloud with completely overcast conditions on the 5 June. In spite of these contrasting weather conditions, the SLS path-averaging method (2-min values scaled to 20 min) showed excellent agreement with the eddy covariance (EC) point measurement (20-min values) method. Both the ECAT and the BR methods showed spikes in their H measurements but there was no evidence of this for the SLS measurements. The spikes occur when there are sudden changes in microclimatic conditions, particularly net irradiance (Fig. 1b). The SLS line-averaged method tends to average such spikes over the beam path length but the ECAT and BR point-measurement systems cannot average. Of particular note is the rather unexpected agreement in measurements for all methods during the night.

A regression comparison between daily (accumulated 20-min) evaporation values for the SLS and BR methods is shown for a period of 201 days (1 Jan to 5 July, 2004) in Fig. 2a. The agreement was fair, with a slope of 0.842 mm mm^{-1} and R = 0.871. The wide bands, represent the confidence belts for a single predicted value and the narrower ones that for the population mean. Much of the variability was attributed to the BR method for which condensation in the early-morning hours result in liquid water in the hoses and mixing bottles invalidating measurements for many hours that day.

The regression comparison between daily (accumulated 20-min) evaporation values for the SLS and EC methods for the same time period showed much less scatter (Fig. 2b). The slope value of 0.874 mm mm^{-1} and R = 0.960 are indicative of the good relationship between measurements from the two methods. Much of the variability can be attributed to the differences between point-estimates of H (the EC method) and line-averaged SLS estimates. The footprint area for all three methods are different and vary according to wind direction, measurement height, stability parameters, friction velocity and H. The fetch distances for the different measurement methods were not the same, and this too would contribute to the measurement differences in H or LE shown in Figs 2 (a) and (b).

All three measurement methods are affected by mist, dew, rainfall and other events that affect the complete transmission of either the SLS laser beam or the EC sonic beam. In the case of the BR measurements, condensation affects the accuracy of the air temperature and water vapour pressure profile measurements adversely. Furthermore, the domes of the net radiometer(s) are often covered with water during such conditions, invalidating the net irradiance measurements.

3.2.5 Comparison of SLS, Eddy Covariance (EC) and Open-path Eddy Covariance (ECopen) Estimates of Latent Energy Flux Density

The latent energy flux density LE was estimated as a residual by using the energy balance equation: LE = $-I_{net}$ - H - F_{soil} where I_{net} is measured using a net radiometer and F_{soil} is estimated from soil heat flux plate measurements and estimates of the heat flux density stored above the plates using soil temperature and soil water content sensors. In the case of the open-path eddy covariance system (ECopen), LE was estimated independently of the other energy balance terms.

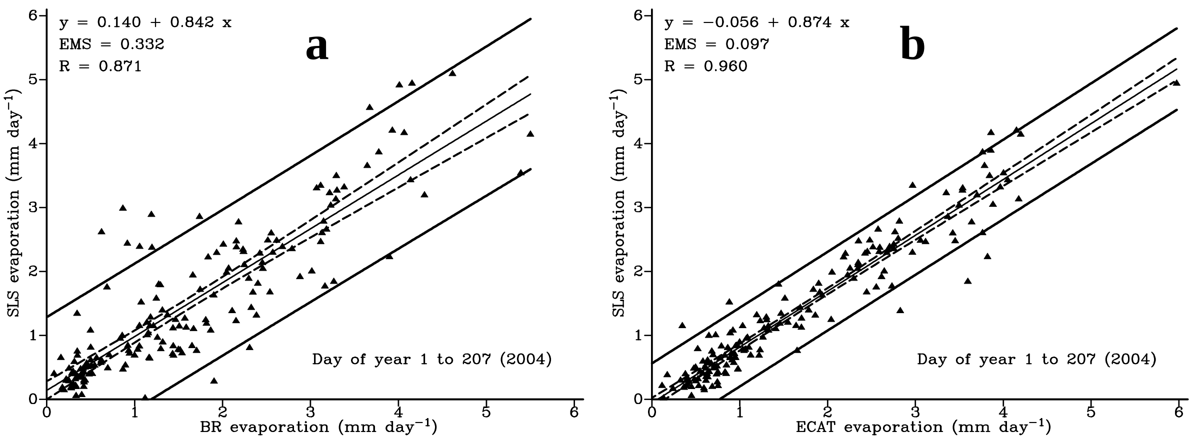

Figure 2. (a, left) Comparisons, for the mixed grassland community, between daily latent energy (evaporation) measurements in mm (taken from the period day of year 1 Jan to 5 July, 2004) for the SLS and BR systems; (b, right) measurement comparisons for the SLS and ECAT systems.
The solid line in both cases is the regression line. The wide bands (solid) represent the confidence belts for a single predicted value and the narrower ones (dotted) that for the population mean.

The agreement between estimates of LE using the independent open-path EC system (ECopen) and the SLS method was poor (data not shown). The reason(s) for this poor agreement needs to be explored further.

4. Conclusions

Three methods, each with a very different theoretical basis and varying from point, to profile and line-averaging estimates of sensible heat show good agreement for a variety of different wind and weather conditions and different canopy heights. The use of the energy balance allowed for the estimation of evaporation. The EC and SLS methods of estimating LE, the former being based on point measurements and the later on line-averaging, show good agreement for a variety of different wind and weather conditions. The Bowen ratio sensible heat and evaporation measurements were more variable than those obtained using the SLS and EC methods. The Bowen ratio method was adversely affected for a longer time period by condensation events due to liquid water in the hoses and in the mixing bottles. This condensation affected the measurements adversely. We conclude that the SLS method is a robust method allowing long-term and continuous evaporation measurements that represent a larger measurement footprint than that for the EC and BR methods.

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